United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NIST Special Publication 919

International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg, MD, February 13-14, 1997 Proceedings

Long T. Phan, Nicholas J. Carino, Dat Duthinh, and Edward Garboczi

B.2 Fire Resistance and Residual Strength of HSC Exposed to Hydrocarbon Fire

Jens Jacob Jensen[1], Tor Arne Hammer[1], Per Arne Hansen[2]

[1]SINTEF Civil and Environment Engineering, Cement and Concrete, Trondheim, Norway
[2]SINTEF Energy, Norwegian Fire Research Laboratory, Trondheim, Norway

ABSTRACT:

This paper deals with the evaluation of the residual strength of high-strength concrete (HSC) structural elements exposed to accidental loading as fire. The question is whether a structure retains enough residual strength for continued unaltered or limited use. The after-accident serviceability, residual strength, cost of repair and second-order consequences are all of vital importance for industrial production systems such as the petroleum industry, offshore installations, power plants and transportation systems. This study discusses in particular the fire resistance and residual strength of HSC-reinforced beams exposed to hydrocarbon fire. Research needs are also discussed.

1. INTRODUCTION

Concrete structures for special industrial production systems such as the petroleum industry, offshore installations, power plants and those for transport systems and fortifications, are of particular concern regarding extreme loadings such as hydrocarbon fires and explosions. Accidental situations such as fire and explosions are often linked together. Structural damage, degradation of materials, large permanent deflections and plastic behavior may be accepted to a certain extent by accidental loading. However, the acceptance criteria have to be defined on the basis of safety requirements with respect to hazard protection, after-accident serviceability, residual strength, cost of repair and second-order consequences.

2. RESIDUAL STRENGTH OF HSC BEAMS EXPOSED TO HYDROCARBON FIRE

2.1 Background

The reduction in the compressive concrete strength at high temperatures has been taken into consideration in most existing design codes; however, regulations are in general based on experimental evidence obtained by testing low- and medium-strength concretes under normal fire conditions. More rapid reductions of the compressive strength of high-strength concrete than of low-strength concrete has been observed at relatively low temperatures [9]. The same tendency was observed in both normal-density and lightweight concretes, in tests in which concrete was exposed to temperatures between 20 and 600°C [1] See Figure 1.

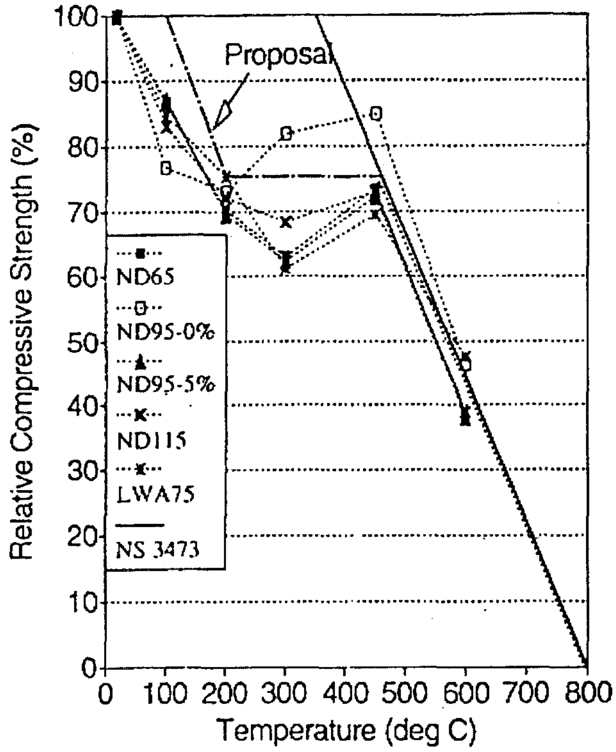

Figure 1. Relative compressive strength vs target temperature of specimens during testing.

The spalling is highly dependent on moisture content. A significant reduction in spalling can be obtained by the addition of polypropylene (PP) fibers to the concrete [2]. This has also been confirmed in structural beam tests [3].

Hydrocarbon fires which are characterized by high temperatures and very rapid temperature rises may cause serious damage to concrete structures. Loss of strength caused by elevated temperatures and spalling damage reduce the load bearing capacity of structural elements. The question which arises after such fires is whether the structure has sufficient residual strength for continued unaltered or limited use.

2.2 Fire Resistance Tests

Fire resistance tests were performed on concrete beams with the dimensions 150 x 200 x 800 mm. A total of 14 beams (11 reinforced and 3 prestressed) of four different concrete types were examined. [3]. Typical reinforcement was as shown in Figure 2. Three of the beams were protected with passive fire protection.

The types of concrete used have the following designations: ND95, LWA75, LWAF75, LWAF75P, LWA50. Where ND=normal density concrete; 95, 75, and 50 refer to the design cube compressive strengths (95, 75, and 50 MPa); LWA=Lighteeight Aggregate concrete, (LWA75: Liapor aggregate, LWA50: Leca aggregate), F= fiber added in concrete mix (Polypropylene, Fibrin type 1825), P=Beam protected with passive fire protection (LightCem LC5).

The different types of concrete and the beam numbers were as follows:

ND95: (61[4], 62[4], 12[3])
LWA75: (21, 22[3])
LWAF75: (31, 32[1], 33[3], 35[2]),(30, 34[3])*
LWAF75P: *(41,* 42[1], 43[2])
LWA50: (51[1], 52)

Legend:
[1]Beam tested with vertical load
[2]Beams without shear reinforcement (Longitudinal reinforcement 3-ϕ20 mm).
[3]Prestressed beams. (Dywidag ϕ26, center)
[4]Longitudinal reinforcement 2ϕ32mm
*Reference beams, not exposed to fire

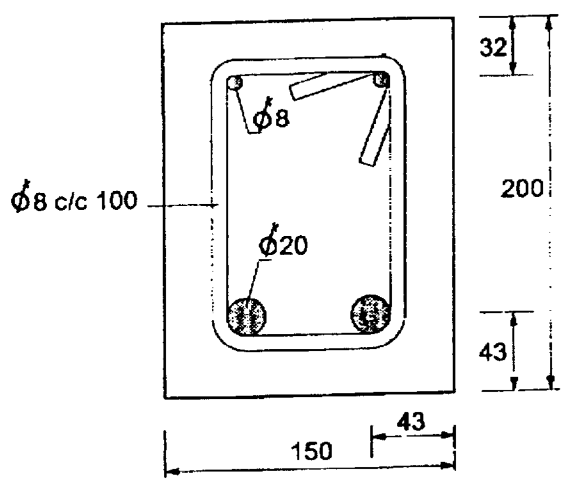

Figure 2. Cross section of typical test beam (21,31,32,41,42,51,52)

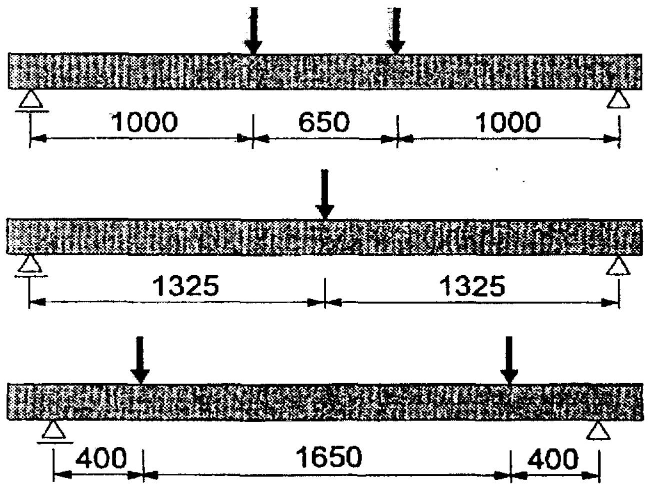

Figure 3. Experimental set-up for testing of residual strength of beams
(a) Nos 30,33,34,52,62 (flexure)
(b) Nos 31,41, and 42 (flexure)
(c) No 43 (shear)

The damage after fire exposure was observed visually. The results may be summarized as follows:

The test results confirmed earlier findings as reported in [5] that severe spalling (exposed reinforcement) occurred on reinforced and prestressed LWA beams. Reduced spalling (spalling, but no exposed reinforcement) of the ND75 concrete beams and normal strength LWA (LWAC50) concrete beams was observed. One of the ND concrete beams collapsed during testing. Reduced or no spalling was observed in the LWAF75 beams. This means that significant improvements in spalling resistance were attained by adding polypropylene fibers to the LWA concrete mix. No spalling was observed on the test specimens with passive fire protection (LWAF75P) [4].

2.3 Residual Strength of Fire-Tested Beams

The residual ultimate strength of seven of the fire tested beams was studied by the structural test arrangement as shown in Figure 3 [41]. None of the LWA75 beams was tested for residual strength because the damage caused by the fire exposure was considered to be too extensive to permit further investigations. Fire testing was conducted on beams 62 (ND95), 31 (LWAW5), 41,42 and 43 (LWAFP75) and 52 (LWA50). In addition the reference beams 30 and 34, which had not been exposed to fire, were tested.

Table I. Failure types and observed and calculated capacities.

Beam No	Failure type	Capacities [KN]		Ratio P_{ex}/P_{th}
	ex/th	P_{ex}	P_{th}	
31	FC/FT	34.3	66.7	0.51
41	FT/FT	68.7	66.7	1.03
42	FT/FT	67.7	66.7	1.01
43	SH/SH	58.9	53.0	1.11
30*	FT/FT	44.1	45.3	0.97
33	FT/FT	13.7	31.6	0.43
34*	FT/FT	43.2	31.6	1.37
52	FC/FC	14.2	38.1	0.37
62	FC/FC	24.0	62.7	0.38

* Reference beams

Types of failure:
FC = Flexure compression
FT = Flexure tension
SH = Shear failure

The test results (ex=experimental) are compared with the calculated (th=theoretical) values for unexposed beams in Table I. The theoretical capacities were calculated according to NS3473 [10], using a characteristic strength, $f_{cn} = 0.56*f_{c28} + 2.8$ MPa. [16].

The results are also presented in Figure 4 in which the residual strength in terms of the moment capacity of fire exposed reinforced LWAF beams (with fibers) are compared with reference beams not exposed to fire.

It may be concluded that even if the structural elements show only minor spalling after exposure, the reduction in concrete strength and thus in the load-bearing capacity may be severe. The beams with passive fire protection had no visual damage after fire exposure and this is consistent with the measured residual strength of the beams. The positive effect of using passive fire protection to prevent spalling and to reduce temperature rise is obvious, and should therefore be considered in design evaluations.

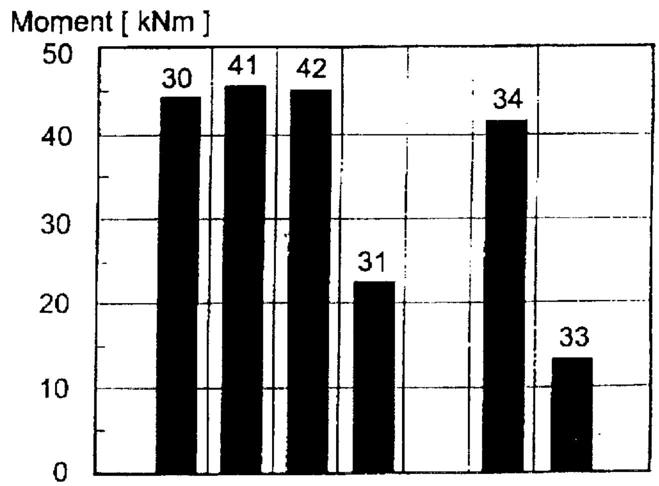

Figure 4. Comparison of residual strength (moment capacity) of fire-exposed reinforced and prestressed LWAF beams (with PP fiber). Beams nos 30 and 34 are reference beams not exposed to fire. Beams nos 41 and 42 have passive fire protection.

3. RECOMMENDATIONS AND RESEARCH NEEDS

3.1 Recommendations

No special recommendations are given for high-strength concrete fire design in Eurocode 2 [14,15]. In the current Norwegian code, NS 3473 [10], special provisions on thermal effects are suggested if the concrete grades are higher than C55. For such grades, it may be assumed, when more precise values are not known, that compressive strength falls linearly from its full value at 100°C to 75% of the full value at 200°C and is constant for higher temperatures until the reduction is as specified for normal strength concrete. See also the proposed recommendation in Figure 1. Similar specifications exist in the Finnish code RakMK B4 [11].

Evaluations of the fire resistance of HSC structures and of the residual strength of structures exposed to fire can be dealt with by means of design methods (material design, adding polypropylene fibers, analysis of temperature development, taking the material properties according to temperature development into account, the use of passive fire protection, structural strength and safety evaluation according to current design methods).

3.2 Research Needs

In spite of the comprehensive investigations carried out, further studies on fire resistance of concrete structures are needed. Special attention has to be paid to the material properties for analysis and evaluation of the **residual strength** of structural elements exposed to accidental loading and fire. The residual strength for continued unaltered or limited use are of importance.

The considerable reduction in compressive strength and E-modulus of HSC at relatively low temperatures (100-300°C) may also cause decreased residual strength of concrete exposed to elevated temperatures in the same range. Further examinations are needed in order to document material properties for design purposes and for evaluation of residual strength of structural elements exposed to fire.

The improvements in spalling resistance by adding polypropylene fibers to the concrete mixture were obvious for LWA concrete. These improvements should be further investigated. By the investigations reported in [2] one special type of passive fire protection was used. Other types of passive fire protection, well suited for concrete structures, have to be examined, eventually refined and/or developed.

The tests performed [2,3]* were carried out under hydrocarbon fire test conditions with temperatures up to 1100°C. Recently higher temperature requirements have been set with temperature rises up to 1300°C. In order to document the fire resistance of concrete and the effectiveness of passive fire protection for the new temperature requirements, additional tests are recommended for documentation purposes.

Accidental situations such as fires and explosions are often linked together. The residual strength of structures damaged by explosion and fire are essential. Accepted methods and criteria for the evaluation of residual strength of concrete structures damaged by explosions and fire are still lacking. Therefore examinations based on the experience obtained through previous research as [17] [Explosion and fire protection (1989)] are recommended.

Research needs: Materials:

- Extend the existing knowledge of temperature dependency of the basic, mechanical properties of HSC (compressive and tensile strength, elastic modulus, stress-strain relationships, residual strengths and elastic properties). Tests have to be performed with different types of aggregates (different lightweight aggregates included) and different types of fibers.
- Optimize concrete mix design in order to prevent spalling (aggregate, additives, fibres).
- Document material properties for analytical approach to the spalling phenomena.
- Update design curves for mechanical properties.

Research needs: Structural elements and structures

- Extension/Revision of existing Codes and Design Standards. HSC has to be included.
- Examination of the fire resistance of structural elements exposed to extreme temperatures (temperatures exceeding the ISO 834 HSC curve).
- Examination of the residual strength of HSC structural elements. Design recommendations for structural evaluation and repair.
- Analytical approach to fire response.

References

[1] *Compresive Strength and E-Modulus at Elevated Temperature.* SINTEF: STF70 A95023.

[2] *Spalling Reduction through Material Design.* SINTEF STF70 A95024.

[3] *Fire Resistance and Spalling Behavior pf LWA Beams.* SINTEF STF25 A95004.

[4] *Residual Strength of Fire-Exposed Structural Elements.* SINTEF STF70 A95025.

[5] Jensen, J.J.; Danielsen, U.; Hansen, A.A.; and Seglem, S.; *Offshore Structures Exposed to Hydrocarbon Fire.* First International Conference on Concrete for Hazard Protection, Edinburgh, September 1987.

[6] Hammer, T.A.; Justnes, H.; Smeplass, S.; *A Concrete Technological Approach to Spalling During Fire.* Paper presented at a Nordic mini-seminar, Trondheim 1989. SINTEF Report STF65 A89036.

[7] Jensen, J.J.; Hammer, T.A.; Opheim, E.; Hansen, P.A.; *Fire Resistance of Lightweight Aggregate Concrete.* International Symposium on Structural Lightweight Concrete, Sandefjord, Norway 1995.

[8] Jensen, J.J.; Opheim, E.; Aune, B.; *Residual Strength of HSC Structural Elements Damaged by Hydrocarbon Fire or Impact Loading.* Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, Paris 1996.

[9] Diederichs, U.; Jumppanen, U-M.; Penttala, V.; *Behavior of High Strength Concrete at High Temperatures.* Helsinki University of Technology, Department of Structural Engineering, Report 92. Espoo 1989.

[10] NS 3473, *Design of Concrete Structures.* 1989 (in Norwegian).

[11] Concrete Association of Finland, *High Strength Concrete. Supplemental Rules and Fire Design RakMK B4.* 1991.

[12] *Fire Design of Concrete Structures in Accordance with CEB/FIP Model Code 90 (Final Draft).* CEB Bulletin d'information No. 208. July 1991.

[13] Eurocode 1: *Basis of Design and Actions on Structures. Part 2-2: Actions on Structures Exposed to Fire.* 1994.

[14] Eurocode 2: *Design of Concrete Structures.* ENV 1992-1-1.

[15] Eurocode 2: *Design of Concrete Structures. pr ENV 1992-1-2 Structural Fire Design* (October 1993).

[16] Sorensen, S.I.; *Concrete Structures - Design According to NS3473/1989*. Tapir, Trondheim, 1989 (in Norwegian).

[17] Haverstad, T.A.; *Passive Fire Protection Subjected to Gas Explosion and Fire Loads*. NTH Dr. ing. Thesis 1989.